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MACHINE CASTING OF FERROUS ALLOYS

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R. Mehrabian, D. G. Backman, Y. V. Murty, G. J. Abbaschian,
S. D. E. Ramati, S. Hong, and R. J. Lauf

Department of Metallurgy and Mining Engineering
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

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R. Mehrabian, D.G. Backman, Y.V. Murty, G.J. Abbaschian

S.D.E. Ramati, S. Hong, R.J. Lauf

University of Illinois at Urbana-Champaign

Department of Metallurgy and Mining Engineering

Department of Mechanical and Industrial Engineering

Urbana, Illinois 61801

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ABSTRACT

This is the second semi-annual report describing research conducted at the University of Illinois at Urbana-Champaign as part of a joint university-industry research program on machine casting of ferrous alloys. It covers a period of six months, April 1, 1976 to September 30, 1976. The work at the University of Illinois was initiated on October 1, 1975, at which time the overall program had already been in effect for 33 months.

This report covers work carried out in the past six months on the following subjects. (1) The various casting systems built during the first six months of the contract period were modified and improved. A new technique was developed for the production of Rheocast ingots of low temperature alloys semi-continuously. A 400 ton Lester cold chamber horizontal die casting machine was acquired and is being installed for future experiments. (2) The important variables in a continuous slurry producer, a Rheocasting apparatus, were identified and the relationship between these variables and the structure of the primary solid particles in slurries of Sn-15%Pb alloy and X-40 cobalt base superalloy was determined. These structures were compared to conventional dendritic structures solidified under identical average cooling rates. (3) The relationship between gating systems, process variables, and mold filling characteristics in a casting machine were established through transparent mold filling studies using dimensionless numbers.

The direct chill casting assembly located below the low temperature continuous slurry producer permits production of small semi-continuous ingots of Sn-15%Pb alloy at volume fraction solid as high as ~0.5. The three process variables effecting the structure of continuously produced, partially solid, metal alloys are average shear and cooling rates and volume fraction solid.

Increasing the average cooling rate during primary solidification reduces the size of the primary solid particles in the slurry. The size of these particles is approximately equivalent to primary dendrite arm spacings in castings solidified at equivalent average cooling rates. Increasing shear rate during primary solidification effects the geometry of the primary solid particles--it reduces the amount of entrapped liquid in these particles.

The flow characteristics during die filling in a casting machine can be analyzed by high speed photography using dimensionless numbers. In both a flat plate and a simulated turbine blade die cavity solid front fill can be achieved by increasing the viscosity of the charge material, increasing the volume fraction solid in a partially solidified slurry. Reduced porosity, turbulence and vorticity are observed when a die cavity fills with a solid front. Ingate geometry and location are important variables effecting the mode of die filling, hence the amount of gas entrapped in a casting.

I. INTRODUCTION

This report is the second describing work carried out at the University of Illinois at Urbana-Champaign as part of a joint University-Industry research program on machine casting of ferrous alloys. Work at the University of Illinois was initiated on October 1, 1975 -- at that time, the overall program had already been in effect for 33 months. The initial aim of the program was to plan and test new and innovative processes and develop a machine casting system for ferrous alloys that would produce good quality parts economically and at high speed. The present participants of the program are University of Illinois, Pratt and Whitney Aircraft and Massachusetts Institute of Technology.

Emphasis of the work at the University of Illinois and Pratt and Whitney Aircraft is on processes and casting systems which employ a partially solid alloy as charge material. The program at the University of Illinois is especially designed to establish the processing conditions necessary to produce porosity-free parts and to evaluate the Rheocasting and Thixocasting processes from both a technical and economical point of view.

The specific objectives of the investigations initiated at the University of Illinois include:

(1) development of the important relationships between process variables in the Rheocasting and Thixocasting systems and the quality of the machine cast parts made from the partially solidified slurries,

(2) determination of the effect of cast (Rheocast) structure on microsegregation, homogenization heat treatment response and mechanical properties of ferrous alloys and superalloys, and

(3) evaluation of the economics of the ferrous machine casting process.

During the first six months of this investigation (1) a variety of casting systems were designed, constructed and operated. These included:

(a) a transparent model continuous slurry producer,

(b) a low-temperature alloy continuous slurry producer,

(c) a high-temperature alloy continuous slurry producer, and

(d) a laboratory casting machine which permits direct observation and photography of mold filling.

Work was also carried out to determine the heat treatment response and mechanical properties of Rheocast high temperature alloys. Finally, work was initiated to evaluate the economics of the new ferrous machine casting process.

<u>During the second six month period, research emphasis has been on</u>:

(1) modification and improvement of the various casting systems including the development of a technique for production of Rheocast ingots of low temperature alloys semi-continuously,

(2) determination of the important relationships between process variables and the structure of continuously produced partially solidified slurries. Comparison of these structures with conventionally cast dendritic structures,

(3) determination of the relationships between gating systems, process variables, mold filling characteristics and soundness of parts produced in the casting machine. A large number of experiments were carried out on the laboratory casting machine. The flow behavior of various viscosity fluids and metal slurries was directly observed via high speed photography and related to gating systems and process variables.

(4) Work was continued to determine the heat treatment response of cast (Rheocast) structures and the relationship between microstructure and properties.

(5) Work initiated on the economic analysis of this new technology was continued.

This semi-annual report covers the most important findings to date on the first three topics listed above. Details of work on the remaining two topics will be combined with work presently underway and reported in the next semi-annual report.

II. MODIFICATION AND IMPROVEMENT OF THE VARIOUS CASTING SYSTEMS

The various continuous slurry producers and the laboratory casting machine designed and built in the first six months of this program were modified and improved. Brief descriptions of the original apparatuses were given in our first semi-annual report (1). A detailed description of the improved systems and their operating procedures are given below. In addition, a 400 ton Lester cold chamber horizontal die casting machine was acquired and is presently being installed for future experiments.

1. Low Temperature Alloy Continuous Slurry Producer

The low temperature alloy continuous slurry producer is employed to produce partially solid slurries of Sn-Pb alloys. This system can also be appropriately modified for direct observation of fluid flow patterns during production of slurries of NH_4Cl-H_2O solutions. Figure 1a shows a photograph of the overall apparatus and associated power supply and control systems. Figure 1b shows a photograph of the transparent system used in direct observation of solidification and fluid flow patterns. Results of work on the NH_4Cl-H_2O system were reported in the first semi-annual report (1). The most important findings of this work were: (a) elimination of flow instabilities (Taylor rings) in the lower mixing chamber by utilizing a square cross-section rotor, and (b) the importance of balancing heat flow in the lower mixing chamber to obtain the desired profile (variation) of volume fraction solid in the slurry along its length.

An important new development, in the past six months, was the successful coupling of this machine to a direct chill casting mold for production of semi-continuous ingots of Sn-Pb alloys. A schematic illustration of the low temperature continuous slurry producer and the direct chill mold assembly is shown in Figure 2. Figure 3

shows a 1 3/4" by 3' long ingot of Sn-15%Pb alloy cast at a volume fraction solid of ~0.5. A detailed description of the complete apparatus is presented below.

<u>The continuous slurry producer</u> consists of a multiple chamber crucible with associated heating and cooling systems and a mixing assembly. The crucible is made of tubular stainless steel and contains two distinct regions, the upper (holding) chamber and the lower (mixing) and partial solidification chamber. The temperature of each chamber is individually controlled by automatically regulating the power and coolant inputs to a series of heating and cooling coils located along the crucible length. This control enables alteration of the thermal process parameter.

The upper chamber, functioning as a reservoir, is heated with a helical coil which is controlled to maintain the metal temperature above its liquidus. The lower mixing chamber is equipped with multiple heating coils each regulated by a proportioning time temperature controller. Four thermocouples are located along its length as shown in Figure 2. Depending upon the desired cooling rate during primary solidification in the lower (mixing) chamber, either air or water is passed through the copper cooling coils. During operation, the temperature gradient in the lower chamber is adjusted so that slurry exiting from the system contains the desired volume fraction of solid.

<u>The mixing assembly</u> shown in photographs of Figure 1 is designed to provide vigorous agitation within the lower (mixing) chamber. It consists of a support system with appropriate bearings and a screw mechanism for lowering and raising of the mixing rotor. As shown in Figure 1a, the height of the mixing rotor is adjusted by a chain driven gear box located on the right side of the apparatus. The rotor itself is usually made of stainless steel with a

square cross section. The present mixing system is driven by a 3/4 h.p. direct current variable speed motor. Rotation speeds are varied between 0 and 1600 RPM.

The flow of the slurry through the system is controlled by adjusting the distance between the rotor bottom and the exit port valve seat. Sn-Pb stock is continuously fed to the top chamber either in liquid or solid form. Production rates in this system can be varied between 2 and 10 lbs/min depending on the heating and cooling rates used in the lower mixing and partial solidification chamber.

The direct chill casting assembly located below the low temperature continuous slurry producer is schematically illustrated in Figure 2. The mold is made of graphite with a slightly tapered cylindrical hole located in its center. The top half of the mold is heated with controlled resistance heating coils while the bottom half is water cooled. This arrangement coupled with vibration of the mold assembly permits production of smooth surface ingots with slurries containing volume fractions of primary solid as high as ~0.5. Finally, a water spray is directed on the ingot as it is withdrawn from the graphite mold by the pedestal and the withdrawal assembly. A photograph of an Sn-15%Pb ingot produced in this way is shown in Figure 3.

Detailed description of the various process variables and their effect on the structure of the primary solid particles in the slurries are presented in a subsequent section.

2. High Temperature Alloy Continuous Slurry Producer

The apparatus originally built was considerably modified to permit production of clean slurries of high temperature alloys. A detailed description of this apparatus and its operating procedure is given below.

(a) Apparatus

Partially solid high temperature slurries are produced continuously by the machine shown in Figure 4 and 5. The production strategy is to melt solid metal fed continuously into the upper chamber of the machine. Simultaneously, in the lower chamber, the alloy is cooled and vigorously agitated to produce a semi-solid slurry composed of spheroidal solid particles suspended in solute enriched liquid. The slurry product is extracted from the lower chamber at a controlled volume fraction solid.

Metal within the system is contained in a crucible made from Vesuvius #235 (58% Al_2O_3, 26%C, and 12% SiO_2). The top (holding) chamber (3 5/8" diameter x 8" high) holds approximately 18 pounds of ferrous or superalloy charge which is inductively heated with a 3 KC, 50 KW motor generator set. The top melt surface is insulated against radiative thermal losses by a sheet of Fiberfrax wool positioned on top of the furnace assembly. A stainless steel tube passes through the insulating covering and is used to provide an Argon-4%Hydrogen atmosphere above the melt surface to prevent oxidation of the molten alloy. The temperature of the top (holding) chamber is maintained above the liquidus and is monitored continuously with a Pt-Pt13%Rh thermocouple sheathed in alumina and suspended in the melt.

The lower (mixing) and partial solidification chamber is cylindrical in shape (1 1/4" I.D. x 6" long). The inside chamber wall and the exit port consist of an alumina combustion tube (1/8" wall thickness) which is cemented to the crucible. Two separate induction coils are located along the outside of the lower chamber to provide both heating and cooling during operation, Figure 5. In order that both functions are accomplished successfully, a controlled thickness of fiberfrax paper and calcined alumina powder is main-

tained between the induction coils and the outside crucible wall. The upper and lower induction coils are powered by a 2.5 KW, 200 KC Lepel power supply and a 20 KW, 200 KC ECCO high frequency power supply, respectively. Three thermocouples are positioned along the outside wall of the crucible to monitor the temperature during operation and to provide a means of control for the various power input levels.

The mixing rotor is a 19" hollow alumina shaft running concentrically to the bottom of the mixing chamber. The lower six inches of the shaft (in the mixing chamber) has a square cross section to promote increased agitation and avoid flow instabilities (Taylor rings) during rotation. The rotor is driven by a 3/4 h.p. direct current motor capable of rotation speeds between 0-1600 RPM. The shaft of the motor is coupled directly to a tach-generator and the motor windings are connected to voltage and amperage meters to enable the measurement of torque and velocity of the mixing rotor. Flow of the slurry is controlled by either raising or lowering the mixing rotor. At its fully lowered position, the rotor rests on the exit port seat, thus stopping flow.

(b) Operating Procedure

Prior to operation of the high temperature slurry producer, the mixing rotor is lowered against the exit port seat and rotated for one half hour in order to establish a mating interface between the two valve components. After this has been done, the rotor is raised 1/8" to accommodate thermal expansion of the alumina rod during heating. Then feed stock is added to the upper holding chamber and power is applied to each of the three induction coils.

During heating prior to the production of for example X-40 cobalt base superalloy semi-solid slurries, 5 KW, 2.5 KW, 4 KW

are supplied to the top, mixing chamber, and exit port induction coils, respectively. During this time, the four thermocouples within the system are monitored to insure that no severe thermal gradients exist within the system. Once the system is completely filled with molten alloy, the power to the mixing chamber induction coil is lowered to ~1/2 KW and the other power inputs are adjusted to prevent overheating of the top bath or the exit port. Rotation is initiated and the rotor is raised and lowered several times to verify that complete valving action is obtained at the exit port.

As the temperature of the metal in the mixing chamber decreases, the rotor is raised periodically and material is discharged to directly assess the volume fraction of solid in the slurry. Just prior to obtaining the desired volume fraction of solid the rotor is permanently raised (approximately 1/8") to establish the desired flow rate. Simultaneously 1/2" diameter solid feed rod is fed into the top chamber whose power input is adjusted to maintain a constant temperature slightly above the liquidus of the alloy processed.

At this stage of operation, the objective is to maintain all system parameters at steady state -- which is achieved by closely inspecting the system parameters; temperature, motor speed, motor torque, and then adjusting the rate of material flow through the machine to maintain a constant level for each parameter. The steady flow of exiting slurry is collected into insulated ingot molds where the material is allowed to fully solidify and cool to room temperature.

This apparatus has been used to produce partially solidified, vigorously agitated, slurries of a variety of high temperature alloys including: bronze, stainless steels and X-40 cobalt base superalloy. Results from some of the earlier alloys processed in this apparatus were presented in our first semi-annual report (1).

Work in the past six months has been carried out exclusively on the X-40 cobalt base superalloy. Results of this study are presented in a subsequent section.

3. Laboratory Casting Machine

A laboratory casting machine was built in the first six months of this investigation. It was modified in the past six months to improve its operation. Photographs of this machine are shown in Figure 6. This apparatus was designed to simulate a commercial cold chamber die casting machine. It is especially equipped to permit direct observation and photography of fluid flow during die filling.

The machine consists of a split die, a locking mechanism, plunger and shot sleeve assembly, and a hydraulic power supply. The dies are fabricated from mild steel plate. One die houses a flat ground quartz window. This assembly coupled with a 16 mm Fasten Movie Camera (capable of film speeds of up to 7000 frames per second) permits direct observation and photography of a charge material as it flows through the gating system into the casting cavity. The shot piston ($1\frac{1}{4}$" O.D.) is powered by a Reed Prentiss hydraulic system capable of 2000 psi pressure. This power supply has two accumulator tanks and automatic controls to regulate both injection pressure and speed. Several machine modifications have been made to improve the operating characteristics of the casting machine. First, the shot sleeve length was decreased to reduce air entrappment in the shot sleeve. Also, the hydraulic cylinder was altered to produce a uniform plunger motion at low plunger velocities. Metal injection velocities at the gate range from a few feet per second to over 250 feet per second.

During operation, either controlled viscosity fluids or Sn-Pb alloys (liquid or partially solid) are fed into the shot sleeve.

During the casting of the low temperature alloys, the shot sleeve is heated by a controlled power supply. The high speed movie camera is activated by an automatic timer connected to a switch on the piston rod.

Two distinct die cavities were used in these studies: (a) a flat plate die cavity, and (b) a simulated turbine blade die cavity. Results from work on the latter cavity are directly communicated to Pratt and Whitney Aircraft so they can optimize their process parameters during production of simulated turbine blades with partially solid slurries of cobalt-base X-40 superalloy.

Detailed account of the results from this work are presented in a subsequent section.

4. Commercial Die Casting Machine

A 400 ton Lester Cold Chamber horizontal die casting machine was donated to the University of Illinois by the Outboard Marine Co. Currently, the machine is being outfitted and instrumented and awaits preliminary testing. The machine will be utilized to confirm the results obtained on the transparent laboratory casting machine under conditions simulating commercial practice. Castings produced in the die casting machine will be subjected to extensive radiographic analysis to relate casting quality to the controlling process parameters.

III. EFFECT OF PROCESS VARIABLES ON STRUCTURE OF PARTIALLY SOLIDIFIED SLURRIES

Control of the structure of partially solidified metal alloy slurries is a most important aspect of this investigation. This structure effects both the rheological behavior of the charge material during the shape forming operations and the subsequent properties of the parts produced in important ways. In order to successfully apply this new technology to casting or forming operations a better understanding of the effect of process variables on the structure, rheological behavior, and properties is necessary. The effect of structure on segregation, homogenization heat treatment response, and properties of castings produced is being pursued in this investigation. Initial results from this work were presented in our first semi-annual report (1). A comprehensive review of past and current work in this area at the University of Illinois will be forthcoming in our next semi-annual report.

Previous fundamental work (2), by one of the authors of this report and an associate, has extensively dealt with the relationship between the structure of partially solidified alloy slurries and their rheological behavior (i.e. apparent viscosity, thixotropy, etc.). In that study, some basic understanding was also developed of the effect of process variables during primary solidification of the slurries in a batch viscometer on the resulting structure.

The general aim of this portion of our present investigation is to not only extend the earlier findings to slurries of alloys produced continuously, but to also compare and contrast these structures with conventionally solidified dendritic structures under identical cooling rates. This latter approach is also pursued in our work on segregation, homogenization heat treatment response, and properties.

In what follows we first review the important process variables effecting structure in a continuous slurry producer. These sections are followed by observations made to date on both the low and high temperature continuous slurry producers with Sn-15%Pb alloy and X-40 cobalt base superalloy.

1. Process Variables in a Continuous Slurry Producer

The various process variables effecting structure in a continuous slurry producer were previously defined (1). These will be further reviewed herein, and the methods available for their determination will be discussed. The three important process variables effecting the structure of partially solidified slurries are:

(a) Average Shear Rate

The average shear rate is a function of the rotor geometry, the clearance between the rotor and the lower mixing chamber, and the rotation speed.

(b) Average Cooling Rate During Primary Solidification

This is a function of the thermal profile (for average rate of heat withdrawal) in the lower mixing and partial solidification chamber, and the flow rate of the exiting slurry (or average residence time spent by the alloy in its primary solidification temperature range).

(c) Volume Fraction Solid

This is the volume fraction of primary spheroidal solid particles in the exiting slurry. It is again dependent on the rate of heat withdrawal in the mixing chamber and the rate of flow of material through this chamber. Of course, superheat in the top holding chamber and the heat of fusion of the alloy are the other important parameters.

In a given continuous slurry producer these fundamental system parameters can be altered by changing the machine design and the operating variables (e.g. power input, cooling capacity, flow rate, etc.). The important process variables listed above combine to totally determine the microstructure, viscosity, and the rheological behavior of a partially solidified slurry.

2. Determination of Process Variables in a Continuous Slurry Producer

The average shear rate in the annulus in the mixing chamber is calculated from the following equation (ignoring the downward flow of the material):

$$\dot{\gamma}_{Ave} = \frac{2\Omega_0}{(1-\kappa^2)}\,\kappa \qquad (1)$$

where κ is the ratio of the radius of a round rotor (or equivalent radius of a square rotor to the radius of the mixing chamber (3), and Ω_0 is angular velocity.

For example, in the low temperature continuous slurry producer, the value of κ is:

$$\kappa_{eff} = \frac{\text{perimeter of the square rotor}}{\text{perimeter of the mixing chamber}} = 0.86$$

At a rotation speed of 1000 RPM the calculated average shear rate $\dot{\gamma}_{Ave} \simeq$ 692 sec^{-1}.

The torque required to turn the rotor may also be calculated (again ignoring the downward flow of the material) from the following equation (3):

$$T = \frac{4\pi\kappa^2 R^2 \Omega_0}{1-\kappa^2} \int_{z=0}^{z=L} \eta(z)\,dz \qquad (2)$$

where R is the radius of the mixing chamber, z is distance from the top of the mixing chamber, L is the total length of the mixing cham-

ber and $\eta(z)$ is the apparent viscosity of the material in the mixing chamber.

Previous fundamental work (2) on Sn-15%Pb alloys has shown that the apparent viscosity, η, of a partially solidified, vigorously agitated, slurry at high shear rates ($\dot{\gamma}_{Ave} \sim 750\ sec^{-1}$) follows an equation of the form:

$$\eta = \eta_o (1 + 2.5g_s + 10.05g_s^2 + A\exp Bg_s) \qquad (3)$$

where η_o is the viscosity of the liquid, g_s is the volume fraction of solid, A and B are constants depending on the structure of the slurry (average cooling rate at high shear rates $\sim 750\ sec^{-1}$).

Therefore, in principle, if the values of A and B are predetermined for a given alloy system solidifying at a different average cooling rates, and if the temperature distribution in the lower mixing chamber can be determined, then volume fraction of solid in the exiting slurry can be determined and controlled by measuring the torque on the rotor using equation (3).

In practice, however, it is much more convenient to measure the relative torque on the rotor and relate it to volume fraction of solid in the exiting slurry at a given flow rate. The volume fraction of solid in the exiting slurry is determined by quantitative metallography of water quenched specimens.

As previously indicated, this is the technique currently used in our high temperature apparatus to produce slurries of desired volume fraction solid at a given flow rate.

The <u>average cooling rate</u> and <u>volume fraction solid</u> in the slurry are dependent on one another. In general, in a conventionally cast alloy (alloy completely solidified from above its liquidus temperature) the average cooling rate is obtained from the following equation:

$$\epsilon_{Ave} = \frac{\Delta T_s}{t_f} \qquad (4)$$

where ΔT_s is the temperature range of solidification (liquidus minus solidus temperature) and t_f is local solidification time.

Average cooling rate experienced by an alloy in the mixing chamber during primary solidification of a slurry is now defined as:

$$\epsilon_{Ave}(g_s) = \frac{\Delta T_s(g_s)}{t_f(g_s)} \qquad (5)$$

where g_s is the volume fraction of primary solid particles in the slurry, $\Delta T_s(g_s)$ is the difference between the liquidus temperature and the temperature of the exiting slurry, $t_f(g_s)$ is the average residence time of the alloy in the mixing chamber (between the exit port and the height in the mixing chamber where the alloy reaches its liquidus temperature).

It is thus obvious that, for any given alloy, one must first know the relationship between volume fraction solid and temperature in its solidification range before average cooling rates in a continuous slurry producer can be accurately determined. In a binary alloy weight fraction solid can be calculated as a function of temperature from the Scheil equation or the lever rule. The former assumes no solid diffusion, equilibrium at the liquid-solid interface, complete diffusion in the liquid and constant partition coefficient. The latter assumes complete diffusion in the solid. If the densities of the liquid and the solid are not too different, then volume fraction solid and weight fraction solid are approximately equal, and the Scheil equation can be used.

$$g_s = 1 - \left(\frac{T_M - T_L}{T_M - T}\right)^{1/1-k}$$

where g_s is volume fraction solid; T_M, melting point of point of the pure solvent; T_L, liquidus temperature of the alloy; and T, actual temperature in the liquid-solid range.

For more complex alloy systems the relationship between volume fraction solid and temperature is established experimentally. First, a slurry of the alloy is produced at the highest volume fraction solid possible (~0.7 to 0.75) and slowly cooled in an ingot mold until solidification is complete. Now, reheating the alloy to different temperatures in the liquid-solid range followed by a rapid quench delineates the spheroidal solid particles existing at each temperature. Quantitative metallography is now carried out to establish the volume fraction solid of primary solid particles in each specimen and a master curve relating volume fraction solid to temperature in the liquid-solid range is established. This technique has successfully been used in a variety of alloy systems including bronze, steels, and nickel base superalloys (4,5).

An alternative method is to put a thermocouple at the exit port of the continuous slurry producer such that the exact temperature of the exiting slurry can be determined. Direct water quenching of the slurry coupled with quantitative metallography, as in the case above, would again give the desired data.

In the low temperature continuous slurry producer, three thermocouples are located directly in the mixing chamber (through the side walls, Figure 2). Therefore, $t_r(g_s)$ and $\Delta T(g_s)$ in equation (5) are directly calculated from flow rate measurements (rate of slurry production) and the recorded temperature profile in the lower mixing chamber. g_s is calculated from equation (6) using the Sn-Pb phase diagram. Average cooling rate during primary solidification is then calculated from equation (5). Figure 7 shows a set of representative curves calculated from thermal data obtained in the low temperature slurry producer during production of Sn-15%Pb alloy slurries.

In the high temperature system the thermocouples are located on the outside wall of the crucible. The location of the liquidus temperature in the mixing chamber is calculated by assuming a con-

stant rate of heat extraction per unit length in the upper portion of the mixing chamber. Average residence time, $t_r(g_s)$ is again calculated by combining the information from above with measured flow rates. $\Delta T_s(g_s)$ is determined by (i) locating a thermocouple in the direct path of the exiting slurry, or (ii) first measuring the volume fraction solid in water quenched drops of the slurry by quantitative metallographic techniques and coupling this information to the experimentally predetermined master curve relating volume fraction solid to temperature in the solidification range of each specific alloy. This latter technique was used in work presented in the next section on X-40 cobalt base superalloy.

3. <u>Effect of Process Variables on Structure</u>

The two alloys studied were the low temperature model alloy Sn-15%Pb and X-40 cobalt base superalloy. Initial results on continuously produced slurries confirm earlier findings (2) that average cooling rate during primary solidification has the most pronounced effect on the size of the primary solid particles. Therefore, a corollary program was carried out to compare these structures with conventional dendritic structures solidified under identical average cooling rates.

Previous experimental evidence (6) indicates that dendrite arm spacing in a given alloy cast from above its liquidus temperature is influenced only by the average cooling rate or local solidification time. Generally, segregate spacing is found to be inversely proportional to average cooling rate to an exponent (or directly proportional to local solidification time to the same exponent). The relationship for a given alloy is:

$$d = at_f^n = b(\varepsilon_{Ave})^{-n}$$

where d is dendrite arm spacing, a, b and exponent n are constants

(different constants for primary and secondary dendrite arm spacing), t_f is local solidification time, and ε_{Ave} is average cooling rate defined in equation (4).

In the corollary experimental program, relationships between primary and secondary dendrite arm spacings were determined for the two alloys of interest to this study. Results of work on the effect of average cooling rate on primary particle size in continuously produced slurries were then compared with the segregate spacings in the dendritically solidified specimens.

Table I lists the experiments carried out to date on the Sn-15%Pb alloy. It lists the process variables used and the measured primary solid particle sizes. Volume fraction solid, g_s, was determined from both the thermal measurements using equation (6), and by standard quantitative metallographic techniques carried out on water quenched specimens. Average primary solid particle size was also measured in each specimen.

Changes in average shear rate, at a given volume fraction solid and average cooling rate, did not significantly effect the size of the primary solid particles, Figure 8. Note that cooling rates were varied between 0.14 and 6.5°C/sec. This confirms earlier findings (2) that the effect of variations in rate of shear on the size of the solid particles in the slurry are only observed at relatively slow cooling rates of $\sim 10^{-2}$°C/sec -- primary solid particle size decreases with increasing average shear rate. However, increasing the shear rate does have an effect on the geometry of the particles. At a given cooling rate and volume fraction solid, increasing the shear rate reduces the amount of entrapped liquid in the solid particles, Figure 9. This observation is in line with previous findings (2) -- reduction in the amount of entrapped liquid results in a corresponding decrease in the effective volume fraction of solid in the slurry, hence its viscosity.

The effect of average cooling rate on the size of the primary solid particles is much more pronounced, Figure 10. Primary solid particle size, p.p.s., in a slurry decreases with increasing cooling rate. This observation is not only in line with previous work on dendritically solidified castings, but our results indicate that the size of the particles in a slurry are approximately equivalent to the primary dendrite arm spacings in conventional castings solidified under identical average cooling rates. Figure 10 also shows the data obtained in our laboratories during conventional solidification of the Sn-15%Pb alloy. The effect of a range of cooling rates, 0.005 to 50°C/sec, on the primary and secondary dendrite arm spacings was determined. This was done by thermal measurements made in 4" tall unidirectional ingots, and thin plate castings made in copper chill, graphite, and insulating models. The corresponding equations to the relationship in equation (7) were determined by a least mean square technique.

$$d = 59.7\varepsilon^{-0.494} \qquad \text{primary} \qquad (8)$$

$$d = 22.97\varepsilon^{-0.346} \qquad \text{secondary} \qquad (9)$$

The data in Table I and Figure 10 are for volume fractions solid in the range of 0.43 to 0.61. Drastic changes in volume fraction solid, for example from 0.2 to 0.6, do result in a corresponding increase in primary solid particle size; however, over the smaller range noted above the effect of cooling rate is much more pronounced. Finally, Figure 11 shows the microstructures of a dendritically solidified and continuously produced (water quenched) slurry of Sn-15%Pb alloy obtained at equivalent cooling rates.

Similar data relating conventionally solidified segregate spacings and primary solid particle size in continuously produced slurries of X-40 cobalt base superalloy are shown in Figure 12. The

linear plots of segregate spacings versus cooling rate were obtained by casting 5" tall unidirectional ingots in exothermic molds, and thin chill plate castings in copper molds, etc. The relationships corresponding to equation (7) for this alloy are

$$d = 90\varepsilon^{-0.32} \quad \text{primary} \tag{10}$$

$$d = 40.4\varepsilon^{-0.27} \quad \text{secondary} \tag{11}$$

Again, the limited data obtained to date, with the high temperature slurry producer, show that primary solid particle size, p.p.s., is close to that of primary dendrite arm spacings obtained at equivalent cooling rates, Figure 12. Note each data point for the slurries is an average from several experiments.

The observations presented above are in line with our studies on the formation of primary solid particles in the NH_4Cl-H_2O system. Solidification, during vigorous agitation, in this transparent system starts with formation of discrete primary dendrite stocks with a few secondary arms attached to each stock. As solidification proceeds, secondary arms remelt, break off, and coarsen. At the same time different particles have a tendency to weld and fuse together. Increasing the cooling rate at the beginning of solidification at equivalent shear rates, results in smaller dendrites and smaller spheroidal primary solid particles in the slurry.

IV. MACHINE CASTING STUDIES

Machine casting studies were undertaken to analyze the relationship between the machine casting variables and casting quality. Two machine casting systems have been developed concurrently to accomplish this goal. The first, a laboratory casting machine incorporating transparent dies, has been used extensively to directly observe the nature of fluid flow during die filling. The second, a 400 ton horizontal cold chamber die casting machine, will be used to determine casting quality under conditions simulating commercial practice. The results from each system will be combined to establish a comprehensive phenomenological relationship between process variables, fluid flow, and casting quality. By developing these relationships, good castings of various geometrics can be successfully produced from partially solid alloy slurries.

Laboratory Casting Machine

The laboratory casting machine is shown in Figure 6. A large number of experiments were conducted during which the machine casting parameters were varied. The process variables examined include:

(1) the kinematic viscosity of the charge material (.003 to 23.0 cm^2/sec, Stokes)

(2) the gate velocity (100 to 8000 cm/sec ~ 2 to ~250 ft/sec)

(3) gate and runner geometry, and location

The effect of charge kinematic viscosity was studied by casting various organic fluids and Sn-Pb liquid and partially solid slurries. The liquids used and their physical properties are listed in Table II. Two casting cavity designs were investigated including a flat plate mold cavity (4" x 2½" x 1/8" thick) and a simulated turbine blade casting cavity. The geometrical features of these cavities and typical runner and ingate patterns are shown in Figures 13 and 14.

The results of experiments conducted to date with both the plate die and the turbine blade die show that the kinematic viscosity of the charge and the ingate velocity influence the pattern of fluid

flow emanating from the ingate. Qualitatively, it was found that at low velocity, high viscosity fluids fill the die cavity with a stable front as shown in Figure 15. However, as ingate velocity increases and charge viscosity decreases, the charge/air interface becomes unstable and atomization of charge occurs at the ingate. At intermediate values of velocity and viscosity, a transitional mode of filling is observed. These die filling patterns are shown in Figure 15.

Physically, the system parameters which influence the stability of the charge/air interface and hence the mode of die filling include

(1) charge viscosity, ν

(2) charge surface tension, σ

(3) ingate velocity, V

(4) charge density, ρ

(5) ingate geometry, a, b

In order to succintly examine the quantitative influence of these parameters, they can be combined into dimensionless groups. The characteristic dimensionless numbers which result from combining the material and design parameters are the Reynolds number, R_E, the Weber number, W, and the Z number, Z, where:

$$R_E = \frac{VD}{\nu} \tag{12}$$

$$W = V\sqrt{\rho D/\sigma} \tag{13}$$

$$Z = \frac{W}{R_E} = \nu\sqrt{\frac{\rho}{\sigma D}} \tag{14}$$

In these equations, D represents the hydraulic diameter which is related to the ingate thickness, a, and width, b, by the following equation:

$$D = 4\,\frac{\text{gate area}}{\text{wetted perimeter}} = 4\,\frac{a \cdot b}{a + b} \tag{15}$$

By representing the mode of die filling observed during each experiment on a plot of Reynolds number, R_E, versus either the Z number or the Weber number, the quantitative relationship between process variables and flow regime can be established. These plots, determined from experiments conducted to date with various fluids, in both of the casting cavity designs, and several runner geometries are shown in Figures 16 and 17. On these plots Regions I, II, and III represent the range of parameters during which solid front fill, transitional fill, and atomized die fill are achieved, respectively. These results confirm the qualitative results described above. For example, from the plot of Reynolds number versus Z number, Figure 16, at a constant value of $Z = 1$, we find that solid front fill is observed when $R_E < 50$ and atomized fill is obtained when $R_E > 300$. At intermediate values of Reynolds number transitional die filling occurs. By definition, a low Reynolds number is synonymous with low gate velocities and high values of kinematic viscosity.

In general, when the die fills with a solid front, air entrappment is minimized within the casting cavity. The minimization of porosity occurs because during the gentle fill, air within the cavity is pushed ahead of the advancing fluid fro t and escapes through the air vents into the overflows. However, when die filling is accompanied by atomization or transitional flow, air is entrapped within the die cavity and both turbulence and vorticity is observed.

During die filling of the flat plate cavity, the flow patterns and the final porosity distribution are both complex at high Reynolds number. At early stages of filling, flow separation occurs along the inside wall of the fan gate, Figure 15c, generating a vortex which is sustained until filling is complete. At this time, gases entrapped within the fan gate rise into the casting cavity. Also, because the gating system employs two gates, a large amount

of turbulence develops due to the mutual impingement of flow from each ingate at high values of Reynolds number. The atomized jets from each ingate finally impact against the forward wall and the fluid rebounds along the outside walls in a direction opposite the incoming jet. This flow pattern continues and two additional vortices and associated gas pockets are observed within the cavity. During the machine casting of metal alloys, early blockage of the air vents prevents the escape of the air entrapped in both the ingate and the die cavity. Typical flow patterns are shown in Figure 18.

During filling of the simulated turbine blade casting, the flow patterns are similarly complex. Three distinct gating patterns were studied to determine the design which will provide the best casting quality. The following gating systems were investigated:

1. transverse filling with three ingates located along the side of the blade.
2. longitudinal filling with one ingate located at the shouldered end of the blade.
3. longitudinal filling with die ingate located at the reduced end of the blade

A considerable amount of air was entrapped when the simulated turbine blade was gated by either the first or the second gate configuration. However, the third gating pattern enabled die filling to proceed with a minimum of entrapped gases. At low gate velocities, high viscosity charge filled the die in a solid front manner. Photographic sequences taken during die filling are shown in Figure 19.

The results of the experiments conducted with the transparent casting system, have shown that the mode of die filling and the amount of gas entrapped during filling are controlled by the physi-

cal properties of the charge material and the geometry and location of the ingates. Specifically, reduced porosity, turbulence, and vorticity are observed when the cavity fills with a solid front. This condition of filling is established at low Reynolds numbers and hence with a low ingate velocity and with charge material having a high kinematic viscosity.

As previously reported (2) the apparent viscosity (or apparent kinematic viscosity) of partially solidified slurries of metal alloys increases with increasing volume fraction of solid; see equation (3). Therefore, it is anticipated that as the volume fraction of solid in the charge material increases solid front fill can be achieved at relatively high gate velocities. A minimum gate velocity exists below which the charge would solidify before the die cavity is completely full. Experiments to date with partially solid slurries of Sn-15%Pb alloy verify the above. Future work will be aimed at: (1) determination of ingate velocities that result in a solid front fill as a function of volume fraction of solid, hence viscosity, of the charge material, and (2) verification of these findings by production and subsequent radiography of castings in the 400 ton horizontal cold chamber die casting machine under conditions simulating commercial practice.

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TABLE I

List of Experiments Carried Out on the Sn-15%Pb alloy in the Low Temperature Continuous Slurry Producer

(a) Average Cooling Rate $\dot{\varepsilon}$ = 0.70 to 0.96 °C/sec

Volume Fraction g_s = 0.53 to 0.61

Run	Shear Rate (sec^{-1})	g_s Scheil	g_s Metallography	Flow Rate (g/min)	Cooling Rate (°C/sec)	Avg. PPS (Microns)
22	140	.57	.68	465	.95	55.0
23	140	57	.67	486	.96	51.3
17	210	60		384	.86	85.4
18	210	61		374	.85	84.1
21	210	56	.62	480	.91	55.7
13	280	59		352	.76	78.6
14	280	56		460	.89	80.5
32	280	60	.64	396	.88	82.9
33	280	57	.69	454	.90	81.0
15	350	.53		444	.76	88
36	420	.59	.66	408	.88	89.2
37	420	.56	.58	486	.92	87.8
19	455	.56	.63	450	.85	68.0
24	455	.54	.63	430	.78	62.1
25	455	.53	.55	480	.83	54
41	630	.57	.51	564	.96	70.1
44	630	.55	.53	414	.81	71.9
45	840	.53	.46	375	.69	87.3
46	840	.58	.57	339	.70	76.9

TABLE I (Continued)

(b) $\dot{\epsilon}$ = 5.15 to 6.47 °C/sec, g_s = 0.45 to 0.55

Run	Shear Rate (sec^{-1})	g_s Scheil	g_s Metallography	Flow Rate (g/min)	Cooling Rate (°C/sec)	Avg. PPS (Microns)
1	420	.49	.60	465	5.15	27.7
2	420	.45	.61	546	5.19	27.4
3	420	.47	.69	550	5.57	25.6
7	665	.53	.50	611	5.52	25
8	665	.57	.59	623	6.47	27

(c) $\dot{\epsilon}$ = 0.14 to 0.32 °C/sec, g_s = 0.43 to 0.48

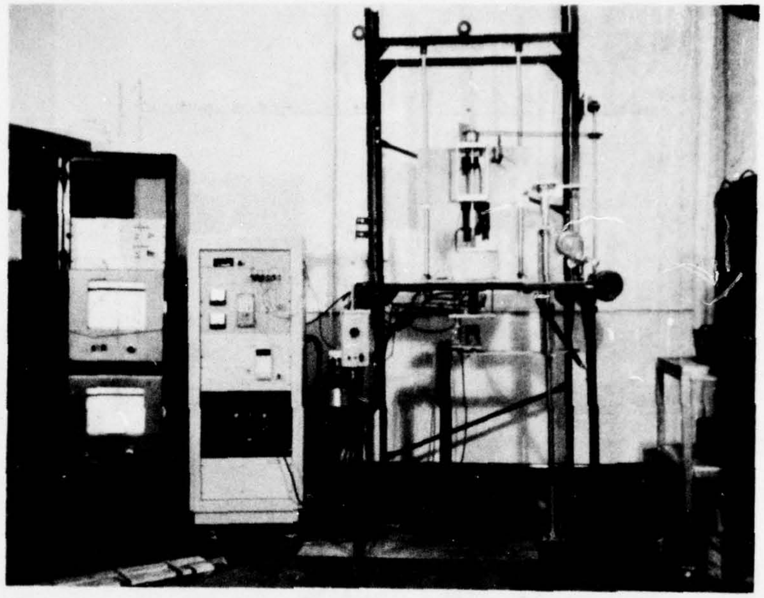
53	770	.48	.46	255	.32	61.7
51	1120	.43	.41	225	.14	70.5
52	1120	.45	.42	165	.18	63.0
54	1120	.45	.37	116	.15	67.5
55	1120	.48	.56	96	.14	65.0

TABLE II

TRANSPARENT CASTING SYSTEM

INJECTED FLUIDS

Material	Density (gm/cc)	Viscosity (Stokes)	Surface Tension (ERGS/cm^2)
Methanol	0.7924	7.55×10^{-3}	23
Hi-Vac Standard 0.1	0.879	0.78	28
Hi-Vac Heavy 0.1	0.880	3.23	32
Glycerine	1.26	11.92	63.4
S-600 Viscosity Standard	0.889	22.97	36.3



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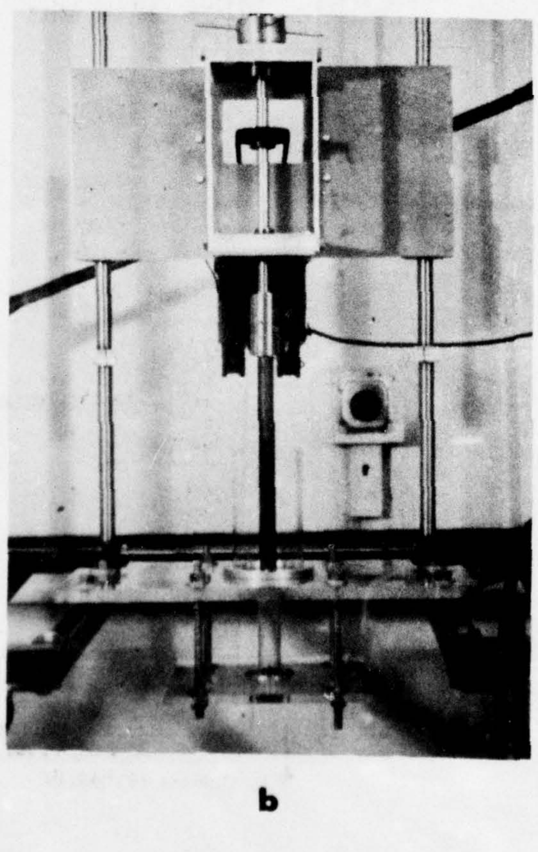


b

Figure 1 . Photographs of the low temperature model continuous slurry producers. Top: overall view of the machine used to produce semi-solid Sn - Pb alloys. Bottom: close view of the transparent assembly used to study the continuous production of NH_4Cl - H_2O semi-solid slurries.

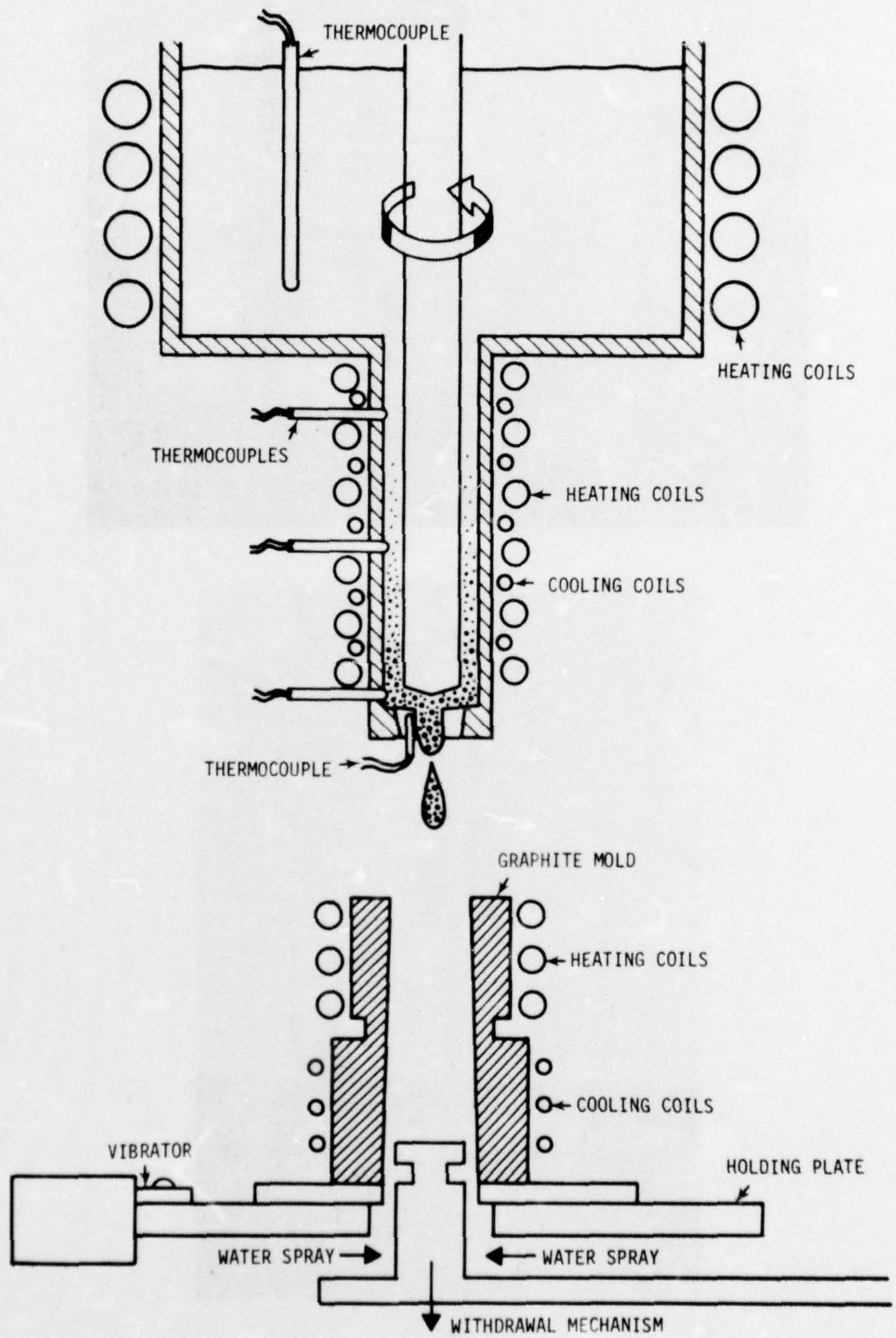


Figure 2. Schematic illustration of the low temperature continuous slurry producer and associated mold arrangement for direct chill casting of semi-continuous ingots.

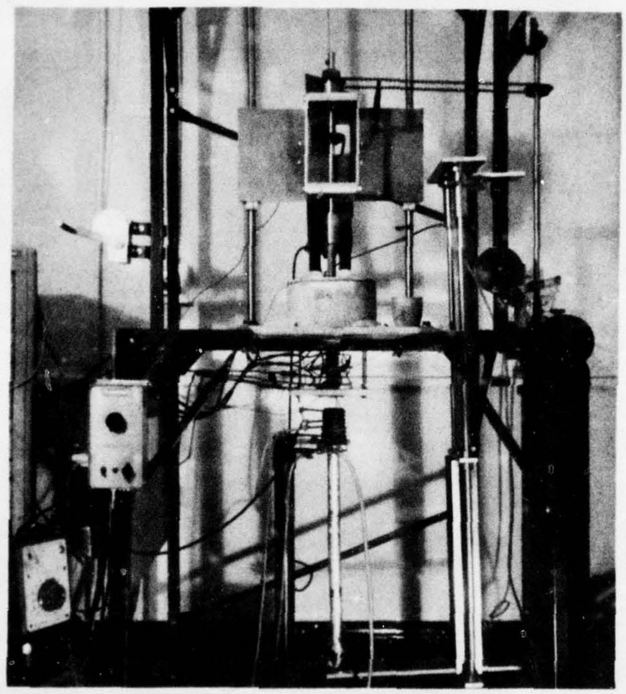
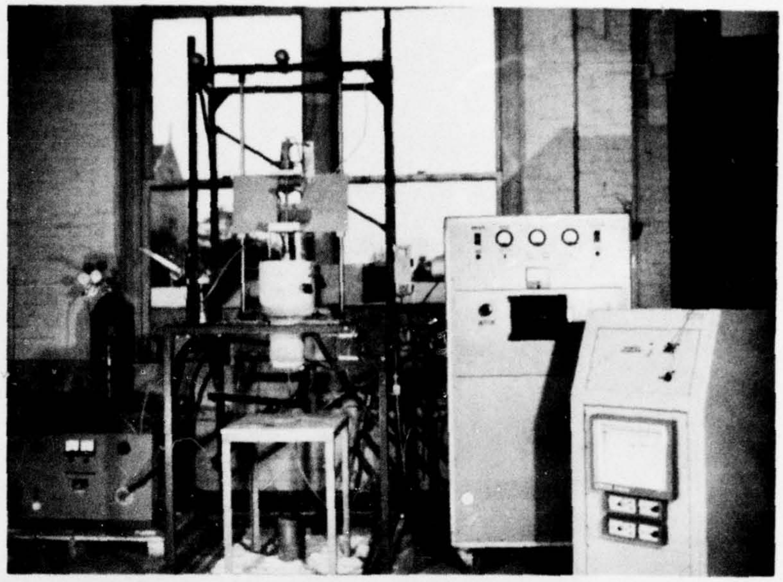


Figure 3. Photograph of low temperature slurry producer showing a Sn-15%Pb ingot cast when the alloy was in the partially solid-partially liquid state.



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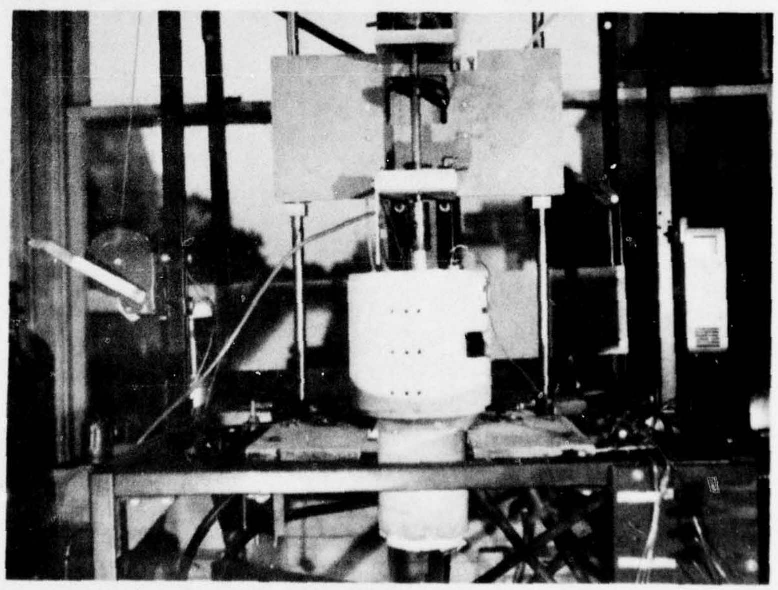

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Figure 4. Photographs of the continuous high temperature slurry producer
Top: overall view showing power supplies, recorder, and slurry producer.
Bottom: close view of the Rheocasting furnace and rotation assembly.

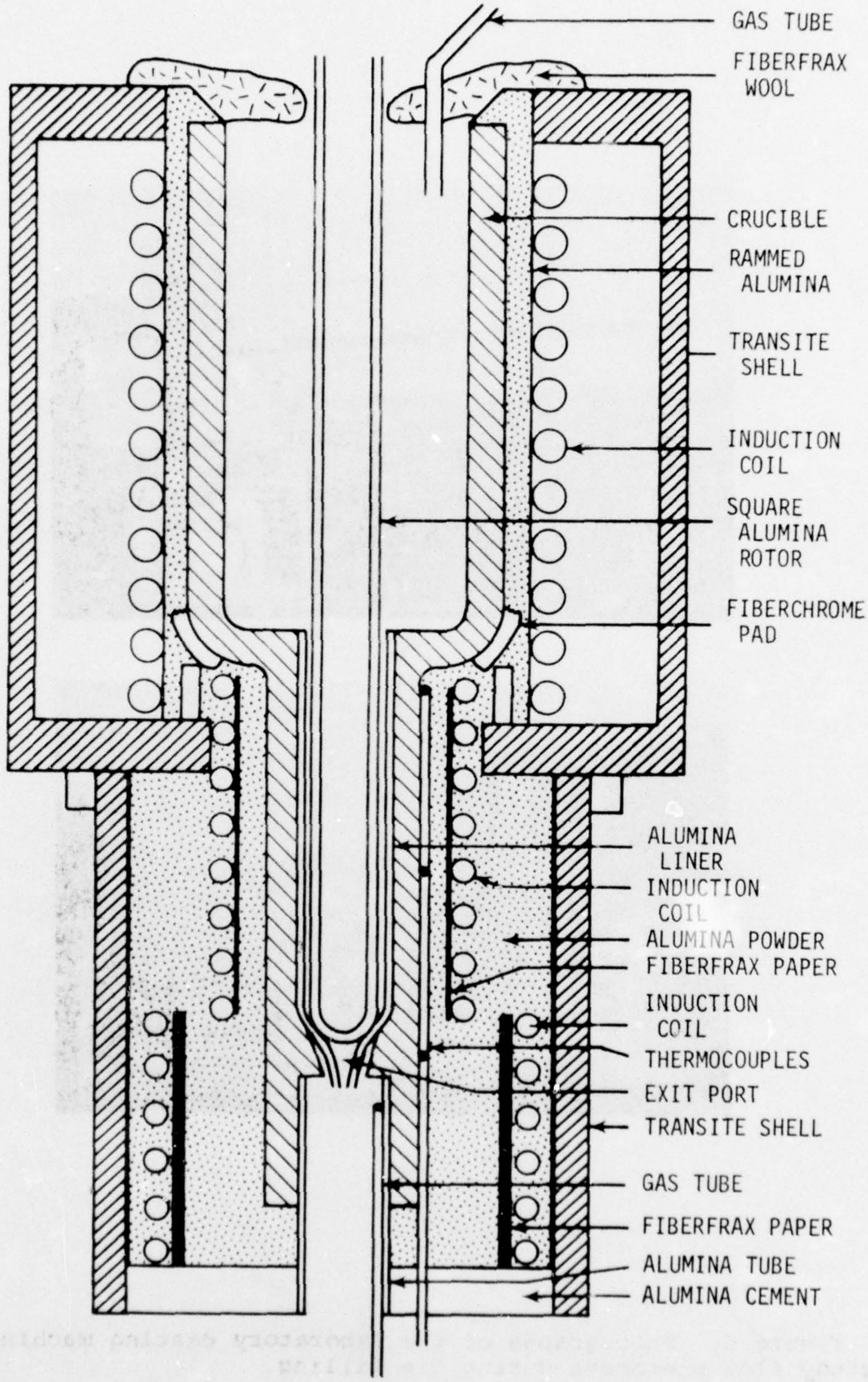
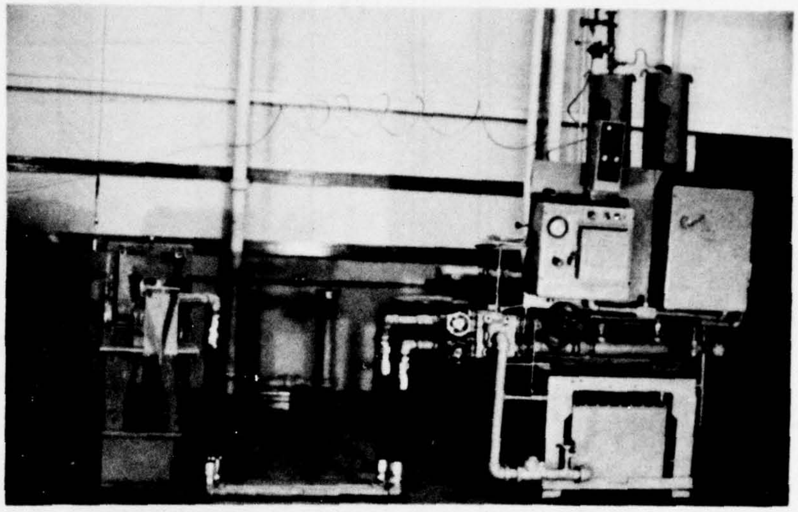


Figure 5. Schematic illustration of the high temperature continuous slurry producer.



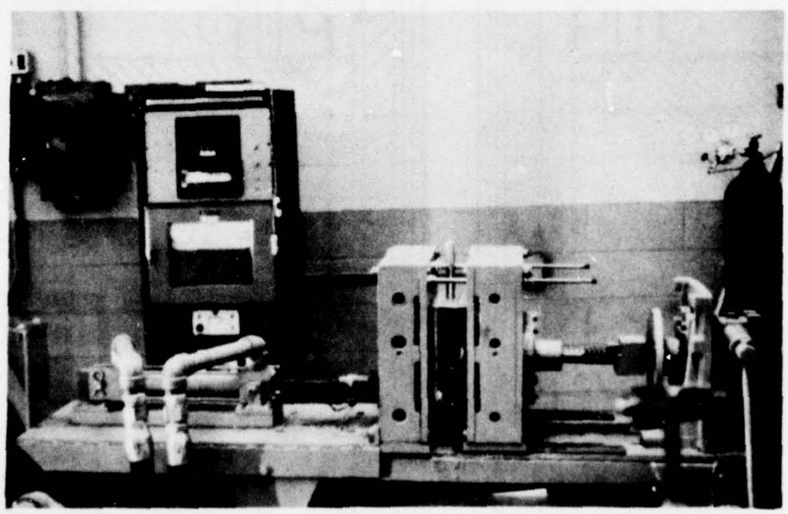


Figure 6. Photographs of the laboratory casting machine used to study flow phenomena during die filling.

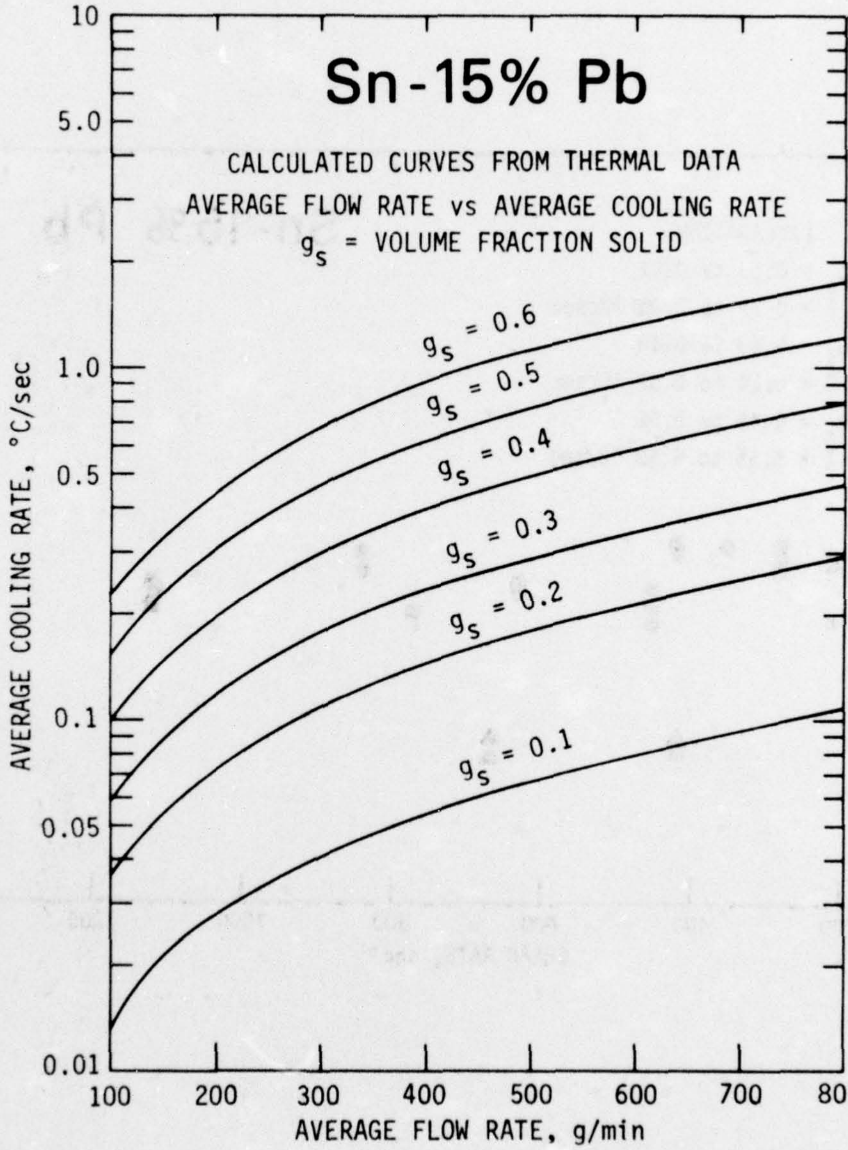


Figure 7. Average cooling rate versus average flow rate at different volume fractions solid determined using equations (5) and (6) and actual thermal measurements made in the low temperature continuous slurry producer.

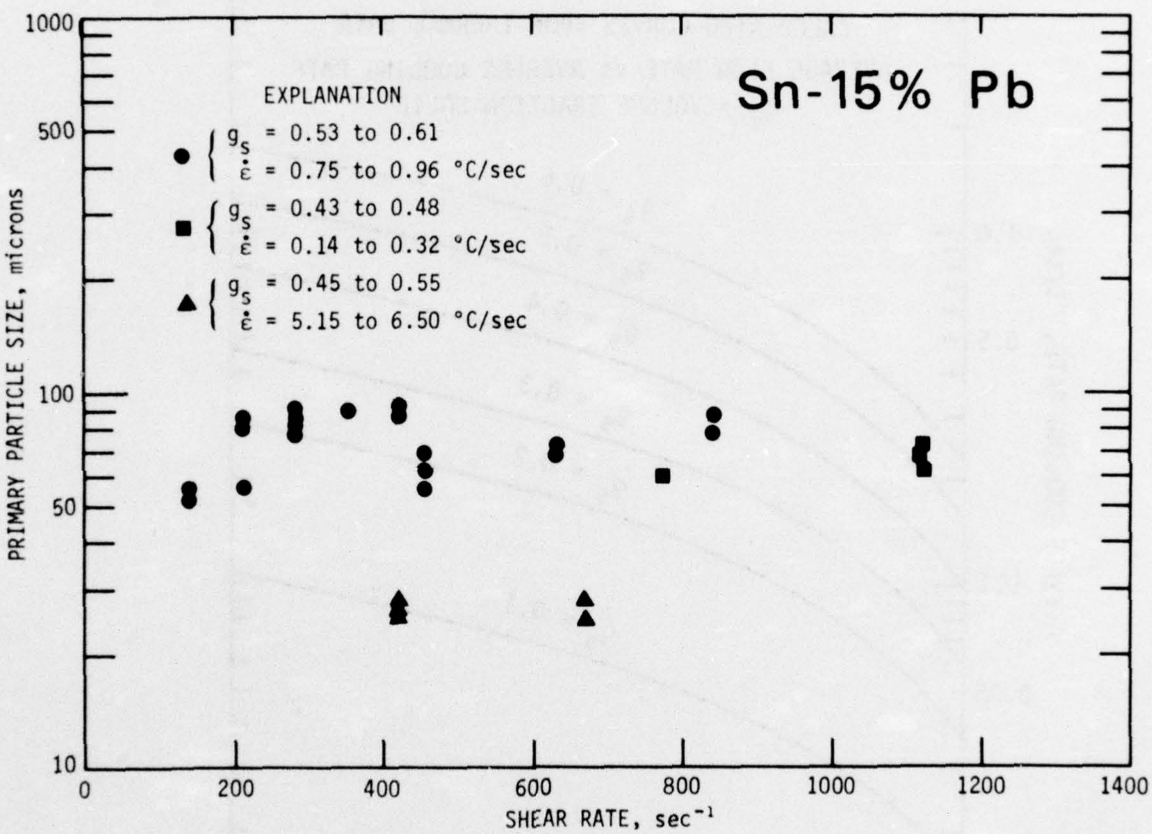
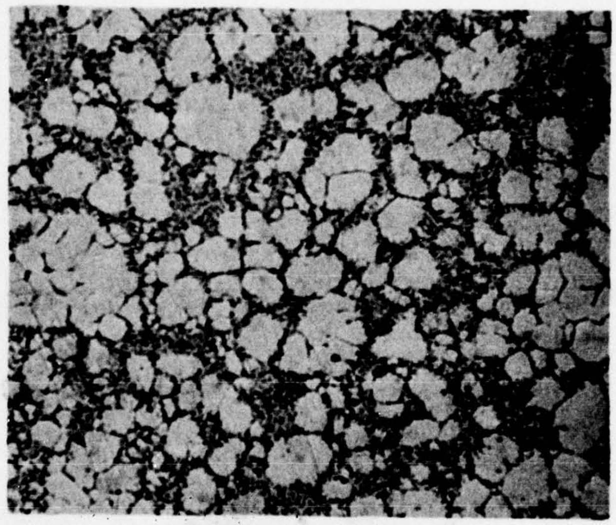


Figure 8. Primary particle size versus average shear rate in continuously produced slurries of Sn-15%Pb alloy. g_s is volume fraction solid and $\dot{\varepsilon}$ is average cooling rate during primary solidification.



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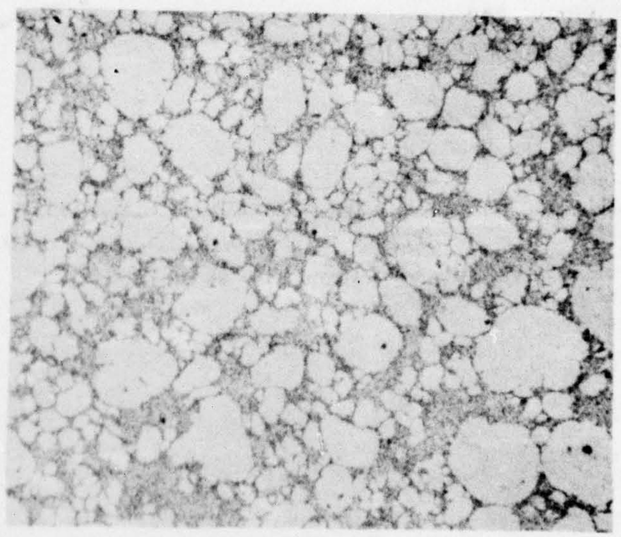


(b)

Figure 9. Effect of shear rate on the size and shape of primary solid particles of continuously Rheocast Sn-15%Pb alloy. Average cooling rate and volume fraction solid in the two specimens were ~0.7° and ~0.6C/sec, respectively; (a) shear rate was 280 sec^{-1}, (b) shear rate was 840 sec^{-1}. Magnification 100X.

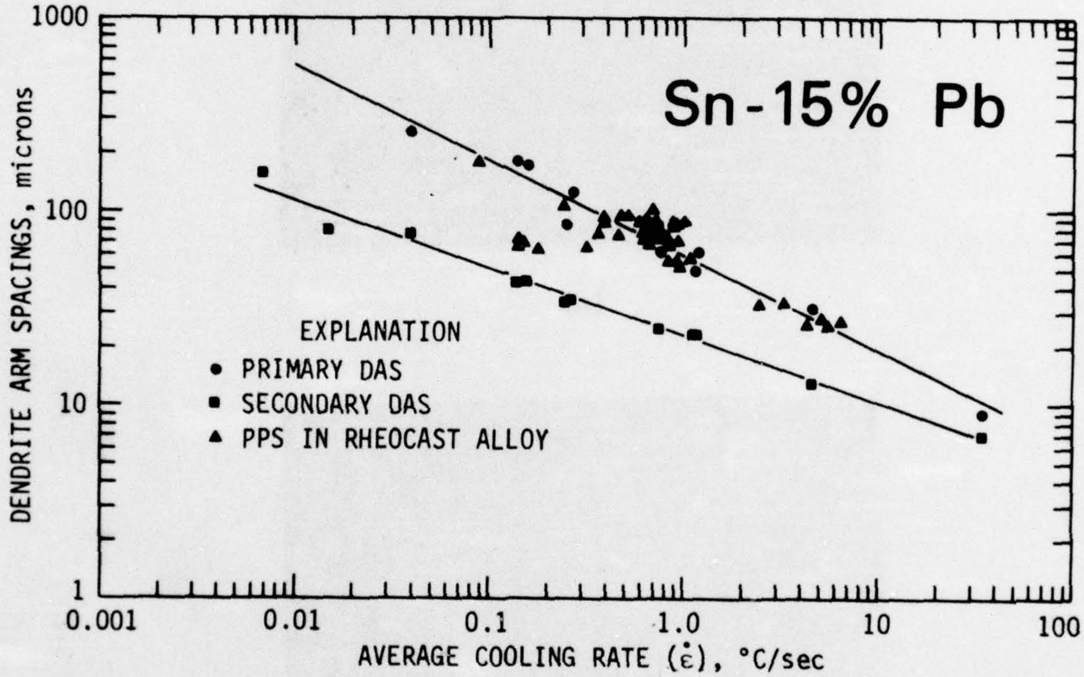
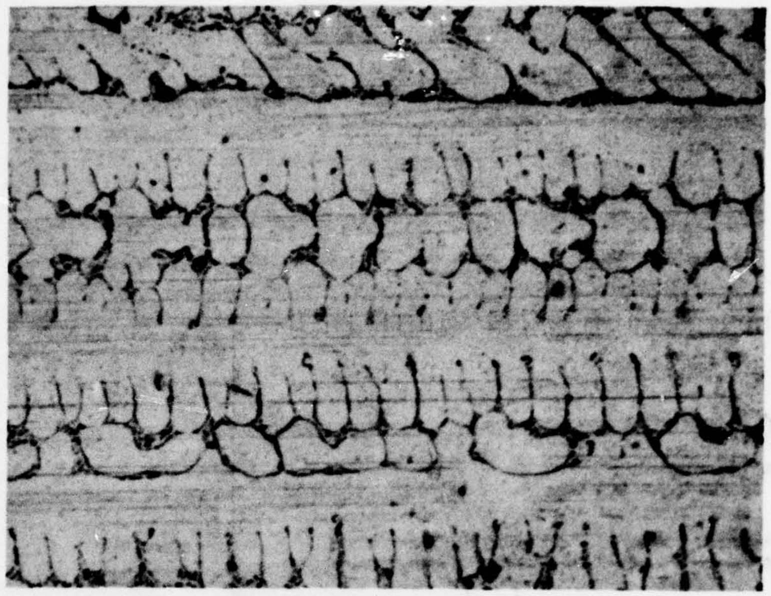


Figure 10. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuously produced slurry of Sn-15%Pb alloy with average cooling rate during solidification.



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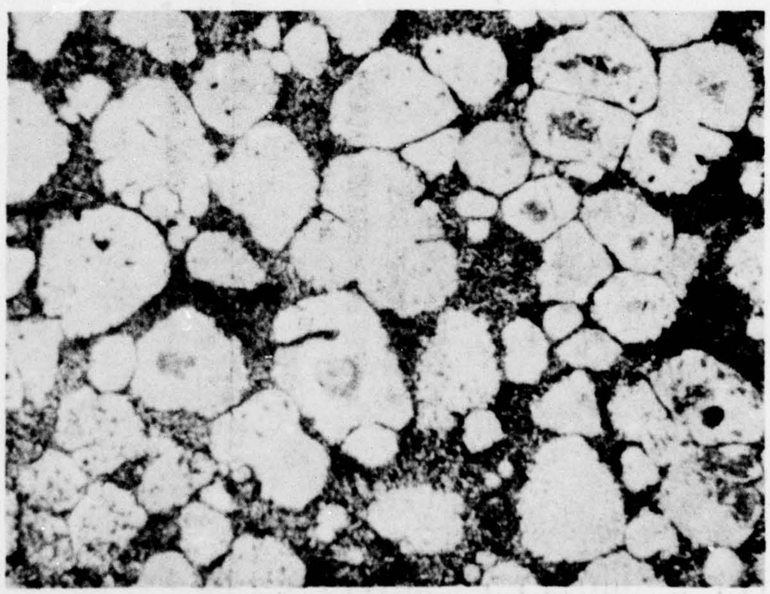


(b)

Figure 11. Microstructures of conventionally solidified (dendritic) and continuously Rheocast Sn-15%Pb alloy. Average cooling rate during solidification of both specimens was ~1°C/sec; (a) conventionally solidified dendritic structure, (b) Rheocast structure, shear rate and volume fraction solid were 420 sec^{-1} and 0.6, respectively. Magnification 250X.

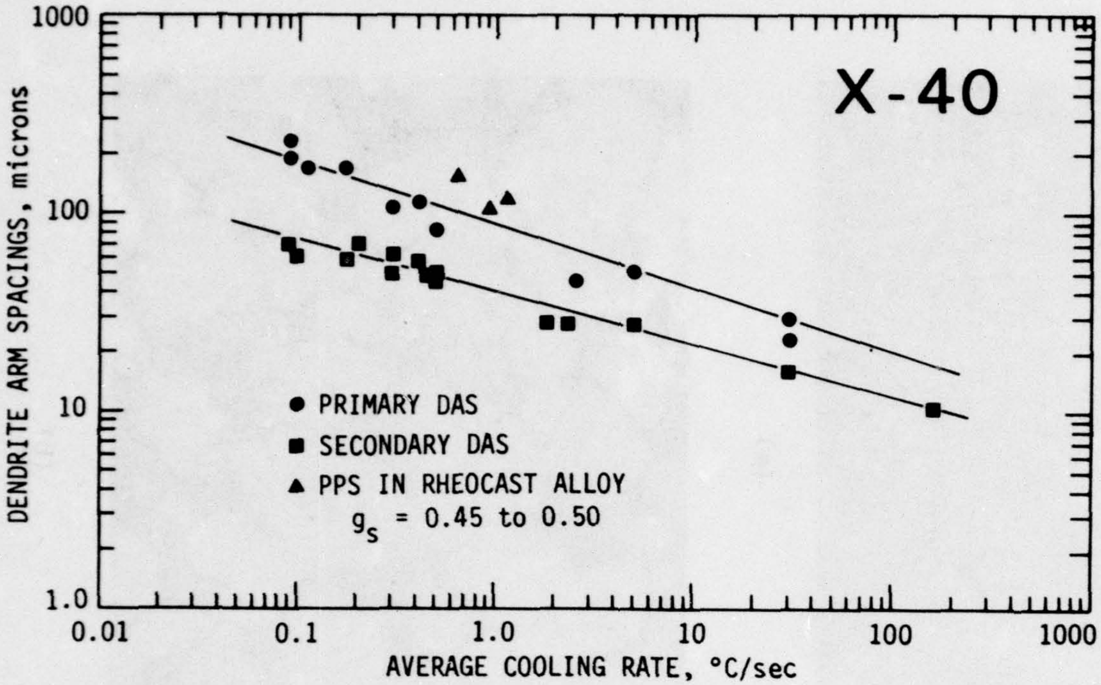


Figure 12. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuously produced slurry of X-40 cobalt base superalloy with average cooling rate during solidification.

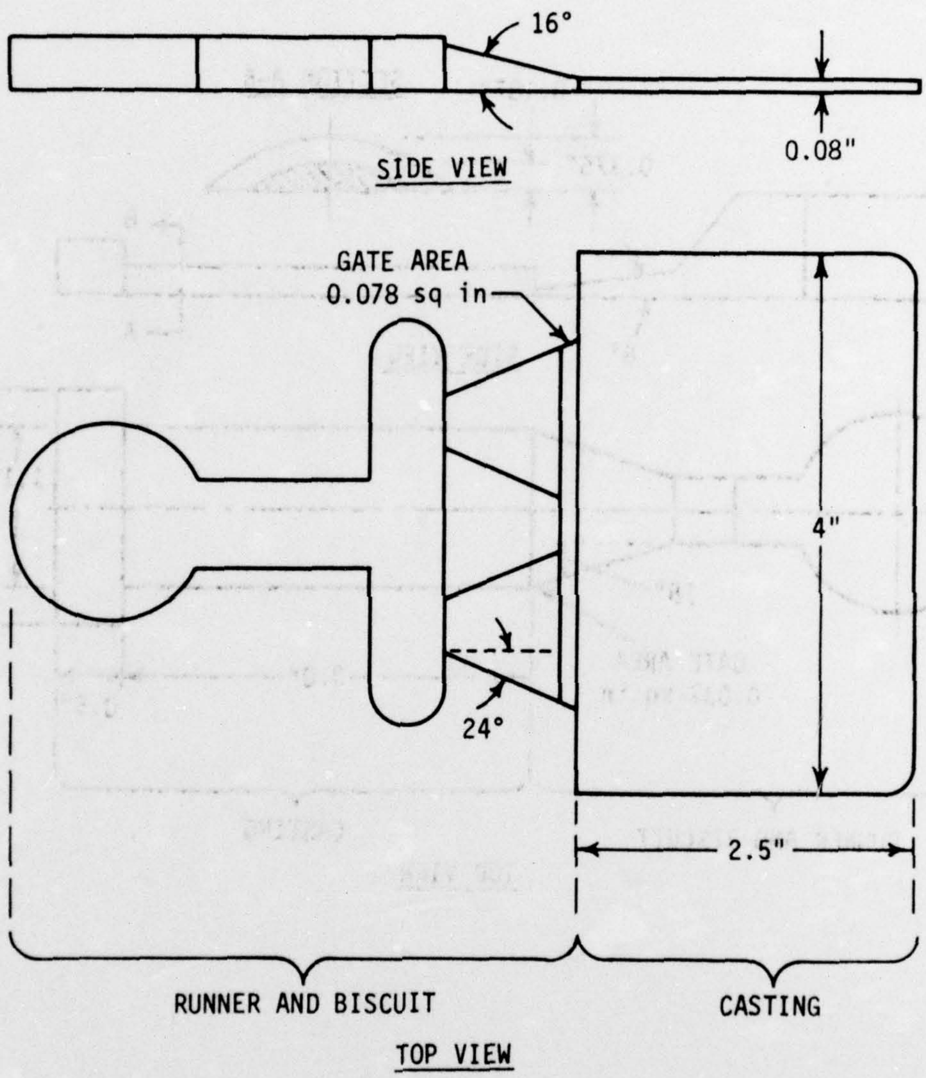


Figure 13. Schematic drawing of the flat plate die cavity configuration used to study the effect of casting variables on the nature of fluid flow during die filling.

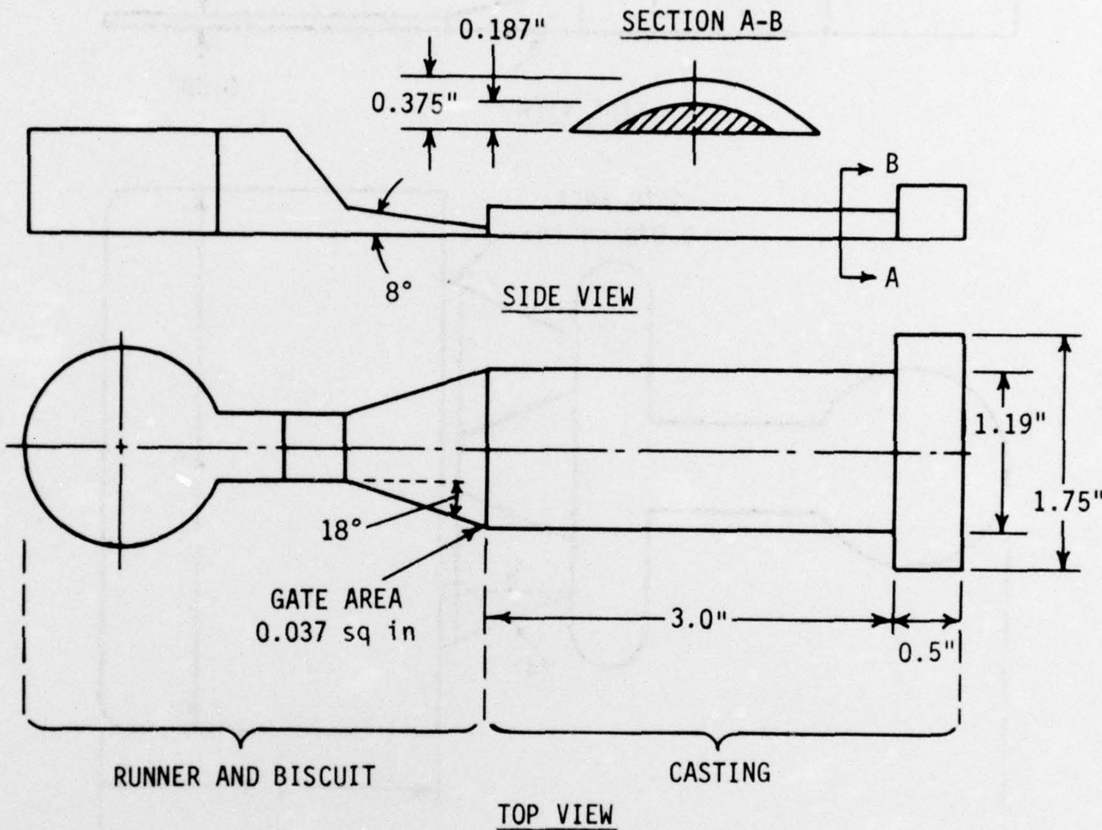
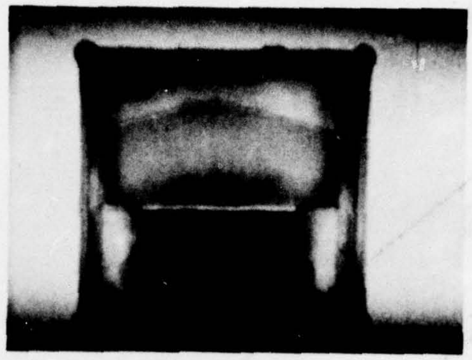


Figure 14. Schematic drawing of the simulated turbine blade die cavity used to study the effect of casting variables on the nature of fluid flow during die filling.



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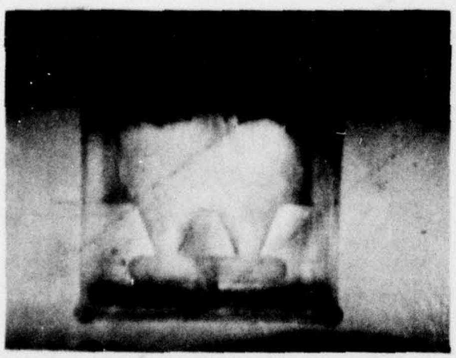


(b)

(c)

Figure 15. Photographs showing the three modes of filling for the flat plate die cavity. (a) Solid front fill of S-600 standard viscosity fluid at an ingate velocity of 12 feet per second, (b) transitional fill of standard HV oil at an ingate velocity of 100 feet per second, and (c) atomized fill of standard HV oil at an ingate velocity of 150 feet per second.

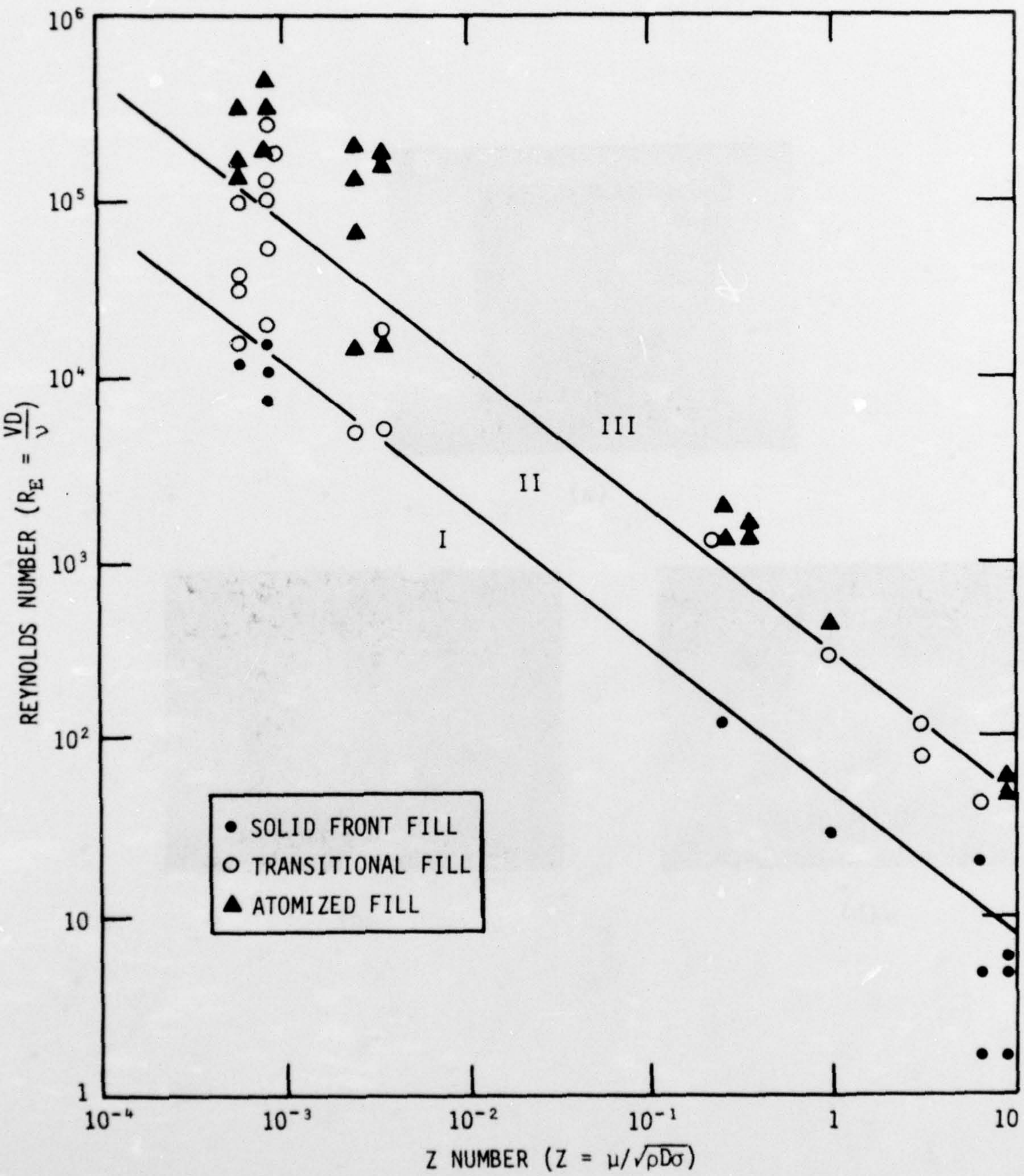


Figure 16. Experimental data obtained, in both of the casting cavity designs, presented in terms of the Reynolds number versus the Z number. This plot permits prediction of the mode of die filling.

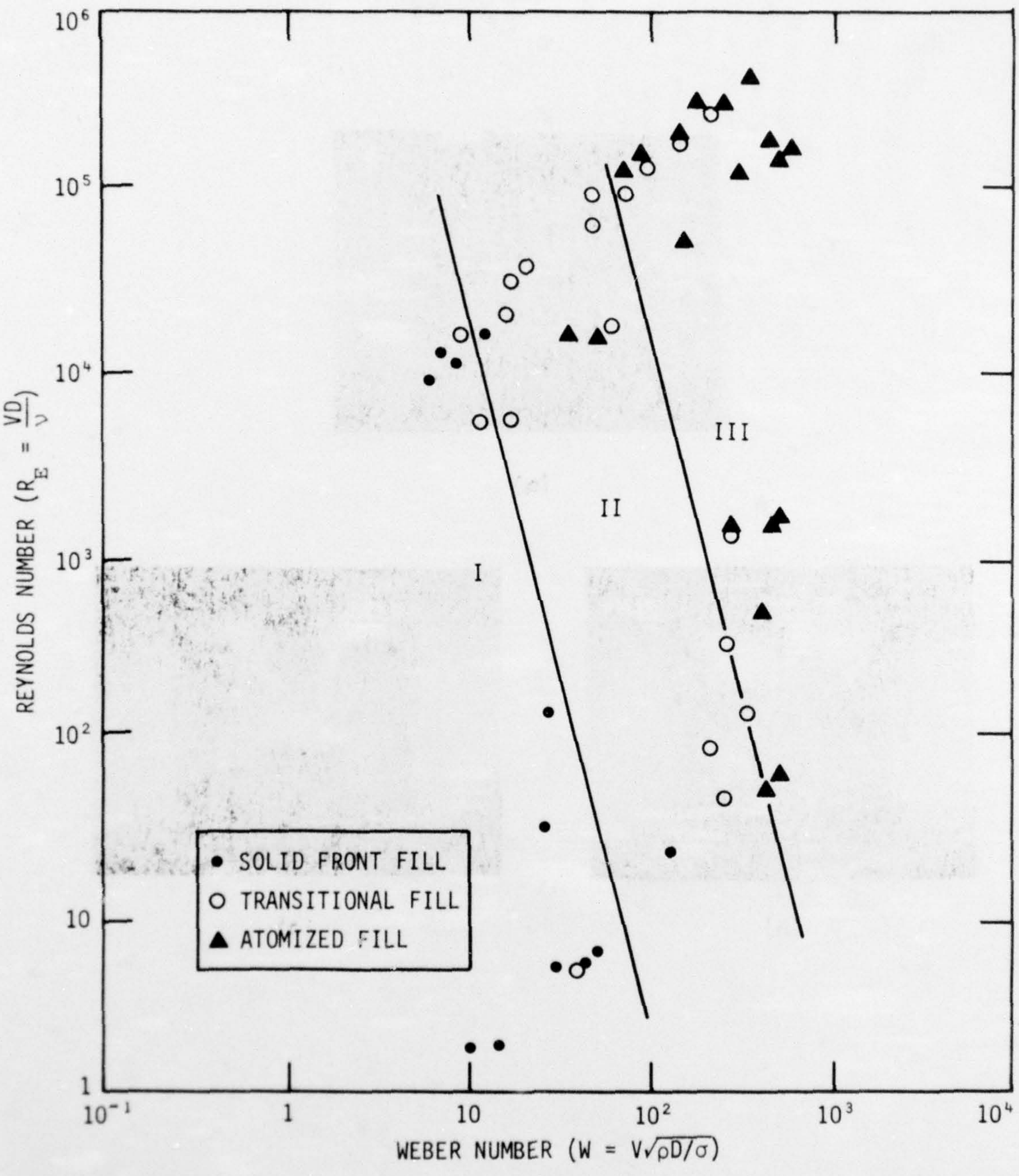
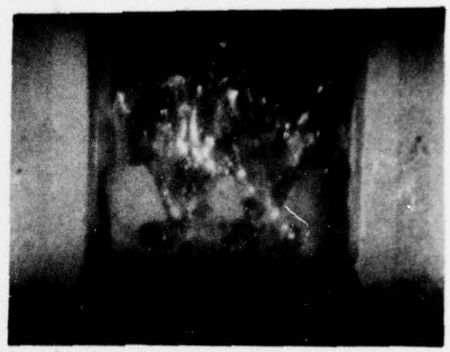


Figure 17. Experimental data obtained, in both of the casting cavity designs, presented in terms of the Reynolds number versus the Weber number. This plot alos permits prediction of the mode of die filling.



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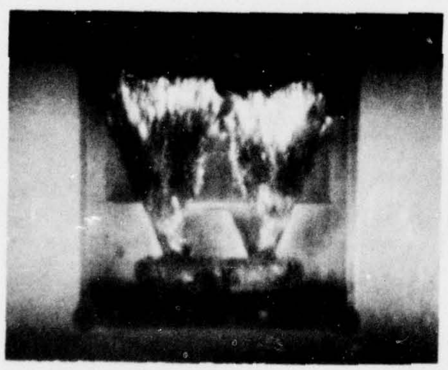
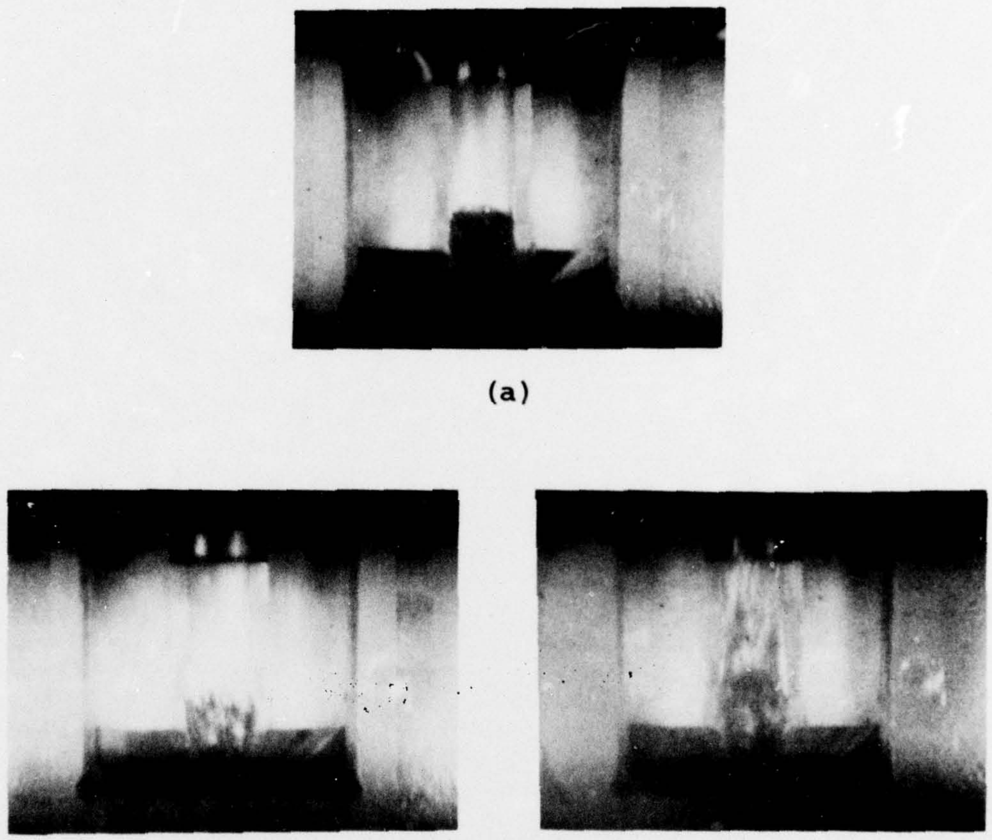


(b)

(c)

Figure 18. Photographs of the flow patterns observed during the casting of superheated Sn-15%Pb liquid alloy in the flat plate die cavity. (a) solid front fill at an ingate velocity of 5 feet per second, (b) transitional fill at an ingate velocity of 50 feet per second, and (c) atomized fill at an ingate velocity of 100 feet per second.



(a)   (b)   (c)

Figure 19. Photographs of the flow patterns observed during the casting of superheated Sn-15%Pb liquid alloy in the simulated turbine blade die cavity. (a) solid front fill at an ingate velocity of 5 feet per second, (b) transitional fill at an ingate velocity of 60 feet per second, and (c) atomized fill at an ingate velocity of 196 feet per second.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the second semi-annual report describing research conducted at the University of Illinois at Urbana-Champaign as part of a joint university-industry research program on machine casting of ferrous alloys. It covers a period of six months, April 1, 1976 to September 30, 1976. The work at the University of Illinois was initiated on October 1, 1975, at which time the overall program had already been in effect for 33 months.

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This report covers work carried out in the past six months on the following subjects. (1) The various casting systems built during the first six months of the contract period were modified and improved. A new technique was developed for the production of Rheocast ingots of low temperature alloys semi-continuously. A 400 ton Lester cold chamber horizontal die casting machine was acquired and is being installed for future experiments. (2) The important variables in a continuous slurry producer, a Rheocasting apparatus, were identified and the relationship between these variables and the structure of the primary solid particles in slurries of Sn-15%Pb alloy and X-40 cobalt base superalloy was determined. These structures were compared to conventional dendritic structures solidified under identical average cooling rates. (3) The relationship between gating systems, process variables, and mold filling characteristics in a casting machine were established through transparent mold filling studies using dimensionless numbers.

The direct chill casting assembly located below the low temperature continuous slurry producer permits production of small semi-continuous ingots of Sn-15%Pb alloy at volume fraction solid as high as ∿0.5. The three process variables effecting the structure of continuously produced, partially solid, metal alloys are average shear and cooling rates and volume fraction solid.

Increasing the average cooling rate during primary solidification reduces the size of the primary solid particles in the slurry. The size of these particles is approximately equivalent to primary dendrite arm spacings in castings solidified at equivalent average cooling rates. Increasing shear rate during primary solidification effects the geometry of the primary solid particles--it reduces the amount of entrapped liquid in these particles.

The flow characteristics during die filling in a casting machine can be analyzed by high speed photography using dimensionless numbers. In both a flat plate and a simulated turbine blade die cavity solid front fill can be achieved by increasing the viscosity of the charge material, increasing the volume fraction solid in a partially solidified slurry. Reduced porosity, turbulence and vorticity are observed when a die cavity fills with a solid front. Ingate geometry and location are important variables effecting the mode of die filling, hence the amount of gas entrapped in a casting.

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